THE MAGNETICALLY DRIVEN IMPLODING LINER PARAMETER SPACE OF THE ATLAS CAPACITOR BANK

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Abstract

The Atlas capacitor bank (23 MJ, 30 MA, 240 kV) is now operational at Los Alamos. Atlas was designed to magnetically drive imploding liners for use as impactors in shock and hydrodynamic experiments. We have conducted a computational "mapping" of the high-performance imploding liner parameter space accessible with Atlas. The effect of charge voltage, transmission inductance, liner thickness, liner initial radius, and liner length, as well as other parameters, has been investigated. Our study shows that Atlas is ideally suited to be a liner driver for liner-on-plasma experiments in a Magnetized Target Fusion (MTF) context.

I. Introduction and Approach

The Atlas capacitor bank [1] will be used to implode magnetically driven liners for impact studies and other applications in the US stockpile stewardship program. Atlas is the successor to the Pegasus capacitor bank that demonstrated that magnetically driven liners are potentially a powerful tool for investigation of physics phenomena at high energy density. Atlas will be able to drive liners to higher energy and higher velocity than Pegasus. In this paper, we summarize a computational study that was conducted to "map out" the imploding liner parameter space that will be accessible to Atlas.

At the time this paper was written, construction of Atlas had been completed and the machine had passed its acceptance tests by successfully delivering a nearly 30 MA pulse to a fixed inductive load located at a radius of approximately 80 cm from the center axis of the machine. The acceptance tests have allowed J. Cochrane of Los Alamos to formulate a fixed element circuit representation of the machine that reproduces the observed current waveform shape very accurately, although the peak current is underestimated by approximately 4% [2]. In this paper, we use the fixed element model, add to it an estimate of the additional transmission inductance that will be required to deliver current to an imploding liner, and couple it to a self-consistent inductance change due to liner motion.

In the computations, the liner is treated as incompressible aluminum. A computation is terminated when the incompressible liner reaches a "target radius," and summary liner parameters, e.g., velocity and kinetic energy, are reported. For the most part, we consider only charge voltages between 135 kV and 195 kV, because the Atlas rail gap switches will not operate reliably at voltages lower than 135 kV and because a voltage swing greater than 115% of the rated voltage (240 kV) will occur for "standard" Atlas loads at voltages greater than 195 kV.

Because we use a simple liner model, we can make no definitive comment about the state of the liner at the time it makes contact with the target, i.e., when it reaches the target radius. However, our experience with one-dimensional magnetohydrodynamic (MHD) computations suggests that Atlas liners will be melted or near-melted if the action integral $\Gamma = \frac{1}{A_o^2}\int_0^t I^2 dt$, where A_o is the initial cross-sectional area of the liner perpendicular to current flow, exceeds approximately 2×10^{16} A^2s/m^4. Therefore, we identify liners for which this value is exceeded.

We also note liners for which impact on the target occurs after current reversal. As the approximately sinusoidal current of Atlas reaches a peak and begins to decrease, the external magnetic field decreases, potentially reaching values below that at the interior of the liner and leading to a deceleration of part of the liner. After sufficient current reversal, the liner is accelerated again. The impact upon liner stability of this deceleration and subsequent acceleration has not been studied. While any stability effect may be minimal because the Atlas current waveform is substantially damped, *a priori* it seems prudent to at least avoid current reversal where possible until the liner stability issue is better understood.

The circuit representation used for the computations reported in this paper is shown in Fig. 1. Atlas has a four-fold symmetry with four groups of three segments. Atlas can also be operated with four groups of two segments or four groups of one, and we explore these configurations as well. The circuit parameters used in the computations of this paper, except where otherwise noted, are listed in Table 1.

The following additional circuit, liner, and target parameters define a single computation: V_o—charge voltage; r_o—liner initial outer radius; δ—initial liner thickness; h—liner height; r_T—outer radius of target, i.e., liner radius at which a computation is terminated.

To verify that our simple incompressible liner model provides adequate predictions of liner performance, we have conducted a series of computations to compare results from the simple model with one-dimensional MHD calculations. In these calculations we used the original design parameters for Liner Demonstration experiment LD-1 [1], the first Atlas liner experiment that

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14. ABSTRACT
The Atlas capacitor bank (23 MJ, 30 MA, 240 kV) is now operational at Los Alamos. Atlas was designed to magnetically drive imploding liners for use as impactors in shock and hydrodynamic experiments. We have conducted a computational mapping of the highperformance imploding liner parameter space accessible with Atlas. The effect of charge voltage, transmission inductance, liner thickness, liner initial radius, and liner length, as well as other parameters, has been investigated. Our study shows that Atlas is ideally suited to be a liner driver for liner-on-plasma experiments in a Magnetized Target Fusion (MTF) context.

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Figure 1. Fixed-element circuit representation of Atlas.

Table 1. Atlas circuit parameters.

# segments	$C(\mu F)$	$L_1(nH)$	$R_1(m\Omega)$	$R_2(m\Omega)$	$R_3(m\Omega)$	$L_2(nH)$	$L_3(nH)$
Three	816	2.6	1.8	50	0.01	6.2	13.2
Two	544	3.9	2.7	75	0.015	9.3	13.2
One	272	7.8	5.4	150	0.03	18.6	13.2

Table 2. Comparison between one-dimensional MHD and incompressible liner models.

	arrival @ r=2 cm				arrival @ r=1 cm			
	time (μs)		velocity (km/s)		time (μs)		velocity (km/s)	
$V_o(kV)$	1-d MHD	incomp.	1-d MHD	incomp.	1-d MHD	incomp	1-d MHD	incomp.
150	12.97	13.05	5.66	5.58	14.60	14.69	6.82	6.85
160	12.27	12.35	6.30	6.20	13.75	13.81	7.70	7.79
170	11.68	11.75	6.89	6.80	12.99	13.07	8.50	8.70

was scheduled for late summer 2001 at the time this paper was written. These parameters are r_o=5 cm, δ=1.3 mm, h=4 cm, L_3=22.15 nH. The computations are summarized in Table 2. Because of the limited number of times at which the one-dimensional results were available, the one-dimensional results are values at potentially as much as 100 ns earlier than actual contact. From Table 2, we conclude that the simple incompressible liner model is adequate to survey the Atlas parameter space.

II. RESULTS

Typical results for LD-1 parameters (r_o=5 cm, h=4 cm, L_3=13.2 nH, r_T=2 cm) are shown in Fig. 2, which shows the computed current for liner thickness values ranging from 0.5 mm to 8 cm. The plotted waveforms terminate at the time the inner surface of the incompressible liner reaches the target radius. For a thickness above 4 cm, the liner does not reach the target until after current reversal. On the other hand, for a thickness less than 1.4 mm, the action integral Γ exceeds 2 x 10^{16} A^2s/m^4, so we would expect thinner liners to be mostly or completely melted at impact.

In Fig. 3 we summarize the results for all machine configurations. The full machine, for example, can in principle operate between curves A and B. Atlas can drive solid liners to a velocity of approximately 10 km/s. For the 4-cm liner height anticipated for most applications experiments, 10% or less of the stored energy is coupled to the liner. Fig. 3 also shows that, for LD-1 parameters, the one-segment configuration of the

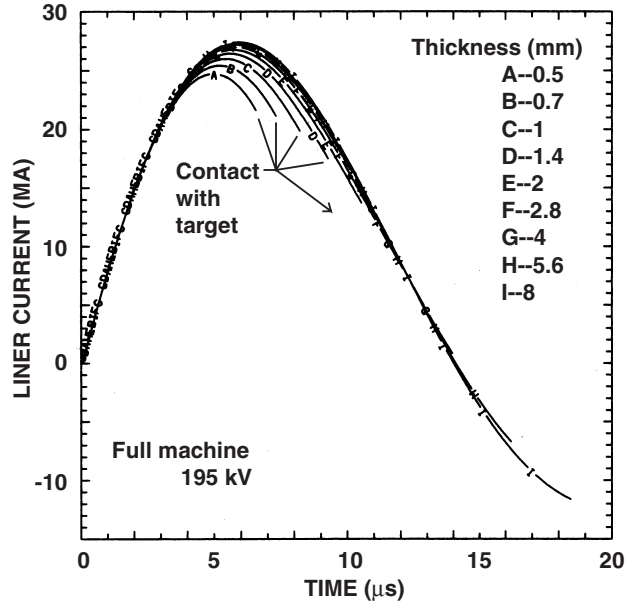machine is useful for solid liners only with impact beyond current reversal.

Figure 2. The liner current at V_o=195 kV, r_o=5 cm, h=4 cm, r_T=2 cm, L_3=13.2 nH.

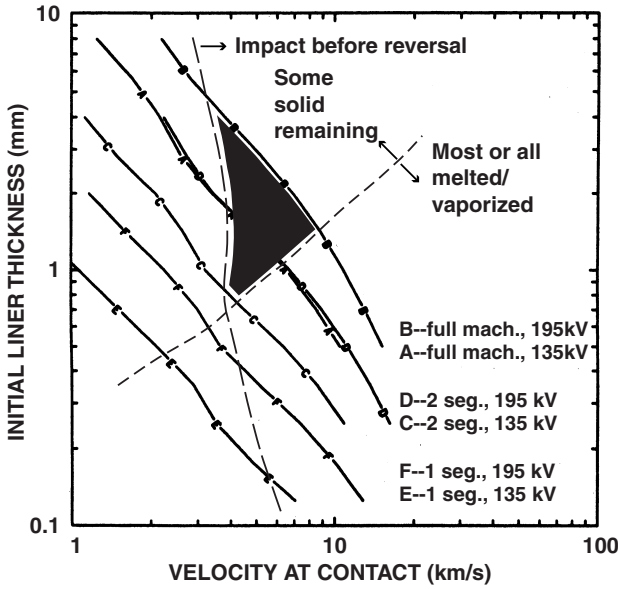The high-current capability of Atlas allows the acceleration of liners to high velocity over a very short

Figure 3. The parameter space for all machine configurations (r_o=5 cm, h=4 cm, r_T=2 cm, L_3=13.2 nH).
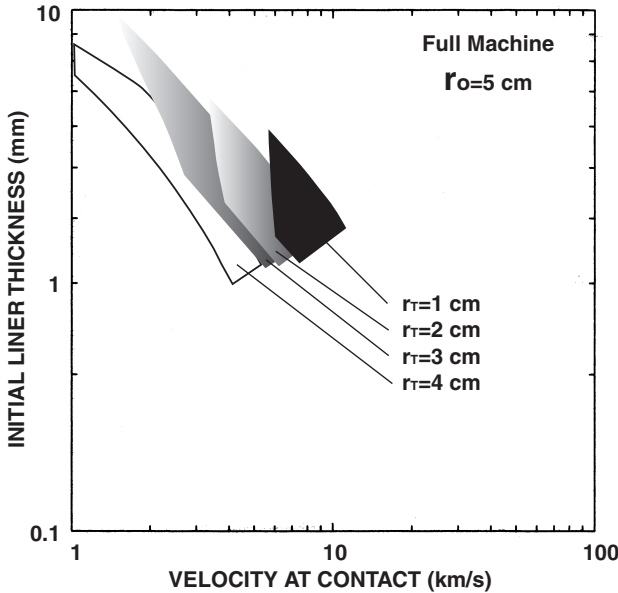

Figure 4. The parameter space for different values of target radius, r_T (r_o=5 cm, h=4 cm, L_3=13.2 nH).

distance. For a fixed r_o and increased r_T, the parameter space enlarges, although the velocity attained at a given liner thickness decreases, as shown in Fig. 4. In Fig. 4, and subsequent figures, the space shown is the area bounded on the lower left by operation at 135 kV, on the upper right by operation at 195 kV, on the lower right by the action integral Γ, and on the upper left by the current reversal condition, in the same way that the space of Fig. 3 is bounded. The parameter space for r_o=3 cm and r_T=2 cm is very broad, as shown in Fig. 5.

As a general rule, the parameter space for LD-1 parameters is not strongly determined by the transition

inductance L_3, as shown in Fig. 6. Calculations where the liner/target spacing is smaller show a greater sensitivity.
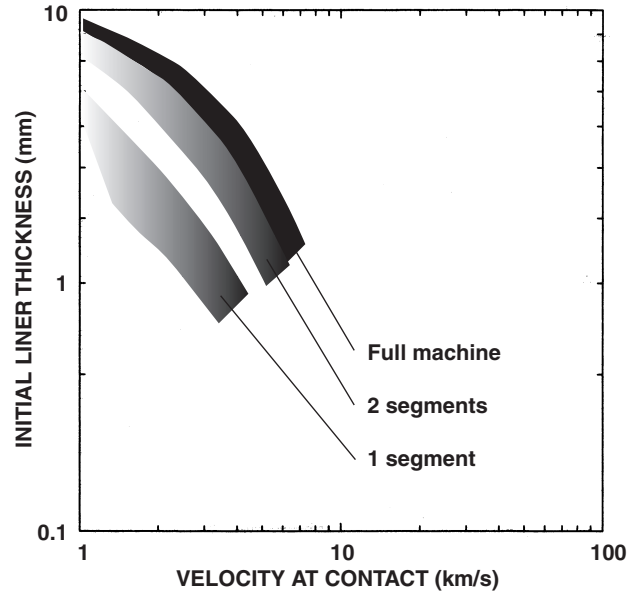

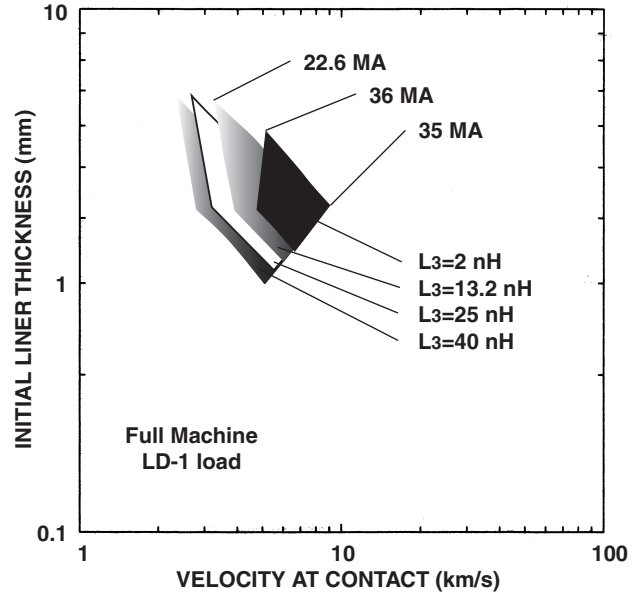**Figure 5.** The near optimum parameter space (r_o=3 cm, h=4 cm, r_T=2 cm, L_3=13.2 nH).

Figure 6. The parameter space for different values of transmission inductance, L_3 (r_o=5 cm, h=4 cm, r_T=2 cm).

III. ATLAS AS AN MTF DRIVER

Magnetized Target Fusion (MTF) is a newly emerging, third "pathway" to controlled thermonuclear fusion [3]. MTF operates at a plasma density and time scale that is intermediate between the twelve orders of magnitude (10^{12}) that separate the two "conventional" pathways, magnetic confinement (tokamaks) and inertial

confinement (lasers and particle beams). In a two-step process, MTF merges features of the conventional pathways. In step 1, a preheated magnetized fusion fuel plasma is established, *a la* magnetic confinement, within a target pusher. In step 2, the magnetized target is imploded and the fusion fuel is heated to fusion temperatures by compressional heating, *a la* inertial confinement.

In one embodiment of MTF, a field-reversed configuration (FRC) is used to form the plasma target. It is beyond the scope of this paper to list the pros and cons of using an FRC. If a suitable FRC can be formed, then the required implosion system will be a 3-10 km/s liner that is approximately 30-cm-long (h=30 cm) with an initial diameter of approximately 10 cm (r_o=5 cm). The successful implosion of such a liner has already been demonstrated [4].

Shown in Figures 7 and 8 are predictions of the Atlas current and resultant velocity for 30-cm-long liners of the type required by FRC embodiments of MTF. The late-time acceleration shown in Fig. 8 is due to liner incompressibility as the liner reaches a radius of less than 5 mm. Liners between 1.4 and 2 cm thick satisfy the melt condition and the voltage reversal limitation at Atlas' full rated voltage of 240 kV. For a thickness, δ, of 1.4 mm, the liner attains a kinetic energy of 10.4 MJ, i.e., 44% of the initially stored energy.

The calculations reported here illustrate the attractiveness of pulsed power driven target fusion: (a) the kinetic energy imparted to the target pusher can be orders of magnitude higher than imparted by lasers or particle beams; (b) the conversion of stored energy into pusher kinetic energy can also be orders of magnitude higher.
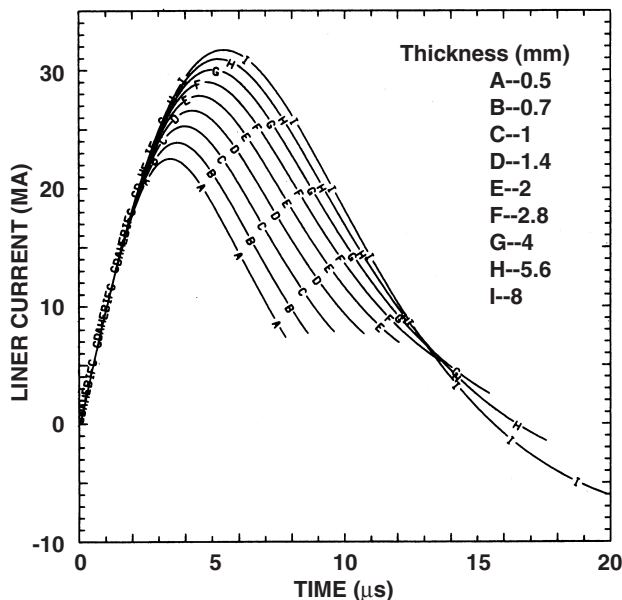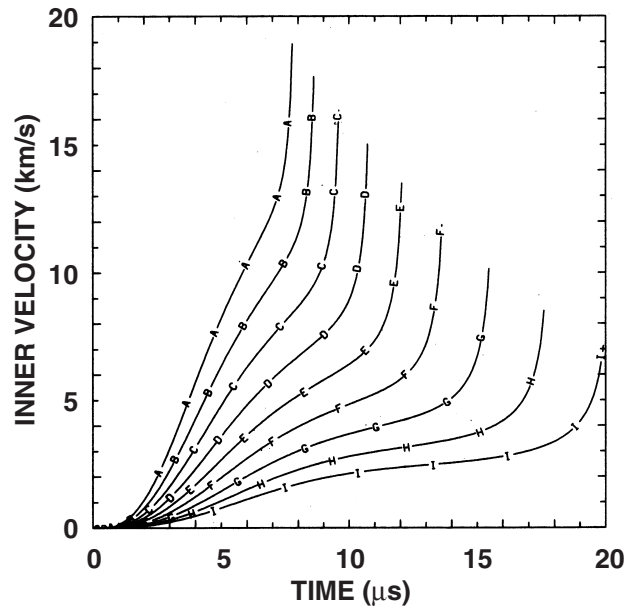

Figure 8. The liner velocity corresponding to Figure 7.

IV. CONCLUDING REMARKS

The computations reported in this paper indicate that Atlas will be a very useful tool for driving imploding liners in a variety of contexts. A number of additional studies would appear to be appropriate including a detailed study of fuse opening switches and other pulse shaping techniques for applications requiring shorter pulse length. It appears that the parameter space for Atlas could be expanded to higher velocity and energy if the damping resistor, R_1, was replaced with, e.g., a safety fuse such as was used on Pegasus and is used on ShivaStar. In addition, it appears that a crow-bar could expand operation and eliminate physics issues associated with current reversal. An evaluation of the utility of melted liners and the stability properties of liners accelerated in the second half-cycle appear to be useful.

V. REFERENCES

[1] see Atlas papers in these proceedings.

[2] J. C. Cochrane, private communication, Los Alamos National Laboratory, 2001.

[3] R. E. Siemon, I. R. Lindemuth, and K. F. Schoenberg, "Why Magnetized Target Fusion Offers a Low-Cost Development Path for Fusion Energy," Comm. Plas. Phys. Cont. Fusion 18 (no. 6), pp. 363-386 (1999).

[4] J. H. Degnan et al., "Implosion of Solid Liner for Compression of Field Reversed Configuration," IEEE Trans. Plas. Sci. 29 (no. 1), pp. 93-98 (2001).

Figure 7. The liner current at V_o=240 kV, r_o=5 cm, h=30 cm, L_3=13.2 nH.